HYP2003 at Jefferson Lab

Hypernuclear Excitation through Kaon Electroproduction

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Collaboration with

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INTRODUCTION

1) (e,e'K+) experiments started at JLab, confirming the great success of hypernuclear production on 12C:

---> Make clear the impact to hypernuclear physics.

2) Novel characteristics of selectively exciting unnatural-parity high spin states:

---> Complementary role to (K−, π−) and (π+,K+)
---> Excite various multiplet states which are not accessible before.

3) High resolution reaction spectroscopy (0.3−0.5MeV)
cf. 2.5MeV for (K−, π−), 1.5MeV for (π+,K+)

---> Helpful tool to investigate dynamical coupling of hyperons to nuclear core excitation.
---> Production of p−defficient hypernuclei which are not accessible.

CONTENTS

1) Basic properties of the $\gamma p \to \Lambda K^+$ process

2) Make clear the characteristics of photo/electro-production of hypernuclei by taking a typical medium-mass target (^{28}Si) with simplified w.f. ($d_{5/2})^{12}$.

3) Show a realistic calculation with the full ($sd)^n$ w.f. for ^{28}Si(γ,K$^+$)$^{28}_{\Lambda}$Al, which should be compared with the coming exp. at JLab.

4) Based on the success of the ^{12}C(e,e'K+) $^{12}_{\Lambda}$B experiment, we present theoretical spectra of producing "proton-defficient" p-shell hypernuclei.

5) Extend the approach to produce heavier hypernuclei A~50, hoping to disclose new areas.

6) Summary

Kinematics and amplitudes for electro-production process

The kinematics of the electroproduction reaction

$$e(p_e) + p/A(p_p/p_A) \rightarrow e'(p_e') + K^+(p_K) + \Lambda/HN(p_\Lambda/p_{HN}) \quad (1)$$

on proton(p)/nuclear(A) target producing Λ hyperon/hypernucleus(HN) is depicted in Fig. 2.

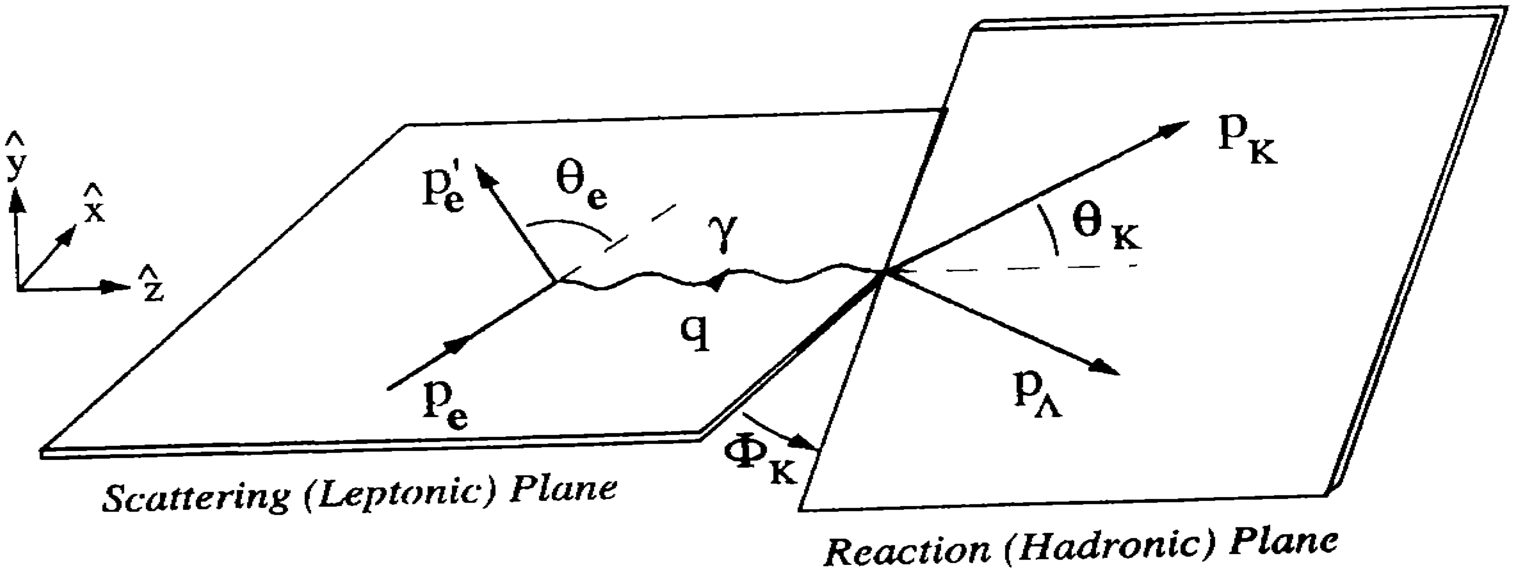
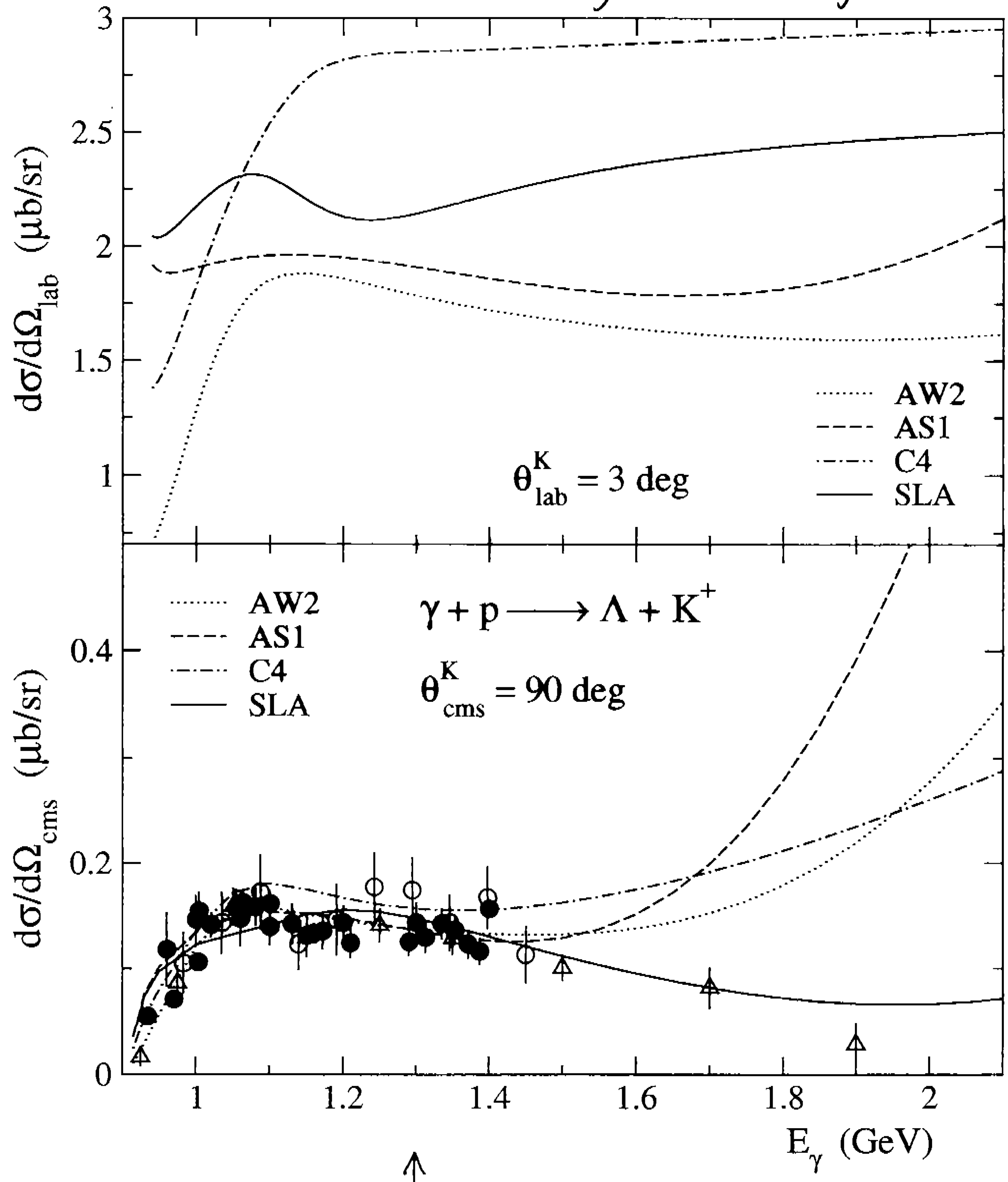


Figure 2: Kinematics of an electroproduction process.

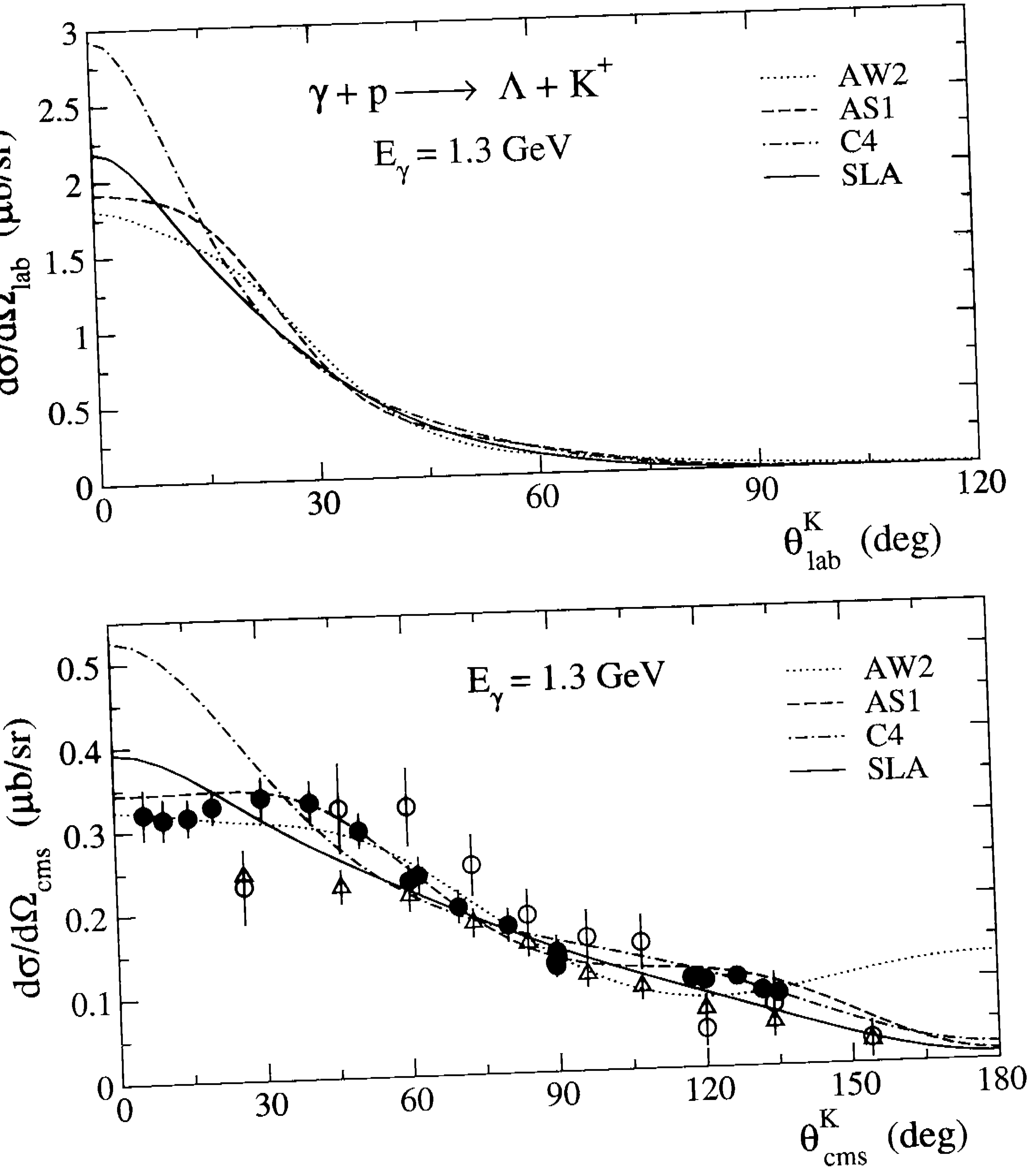
Exp : SAPHIR

AW4 : Adelseck-Wright (1988)
AS1 : Adelseck-Saghai (1990)
C4 : Williams-Ji-Cotanch (1992)
SLA : Mizutani-Fayard-Lamot-Saghai (1998)



↑

$E_\gamma = 1.3$ GeV



γ + p ⟶ Λ + K+
Eγ = 1.3 GeV
AW2
AS1
C4
SLA
dσ/dΩlab (μb/sr)
θKlab (deg)
0
0.5
1
1.5
2
2.5
3
0
30
60
90
120
Eγ = 1.3 GeV
AW2
AS1
C4
SLA
dσ/dΩcms (μb/sr)
θKcms (deg)
0
0.1
0.2
0.3
0.4
0.5
0
30
60
90
120
150
180

Framework of the calculation

The elementary amplitude for the kaon photoproduction $\gamma + p \to \Lambda + K^+$ is written in the 2-body center-of-momentum (2CM) system as

$$\mathcal{M} \equiv \frac{(2\pi)^2}{\sqrt{s}} \sqrt{e_\gamma e_p e_\Lambda e_K} \langle \boldsymbol{q}, -\boldsymbol{q} | t | \boldsymbol{\kappa}, -\boldsymbol{\kappa} \rangle$$

$$= iF_1(\boldsymbol{\sigma}\cdot\boldsymbol{\epsilon}) + F_2(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{q}})[\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{\kappa}}\times\boldsymbol{\epsilon})] + iF_3(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{\kappa}})(\hat{\boldsymbol{q}}\cdot\boldsymbol{\epsilon}) + iF_4(\boldsymbol{\sigma}\cdot\hat{\boldsymbol{q}})(\hat{\boldsymbol{q}}\cdot\boldsymbol{\epsilon}) . \quad (2\cdot1)$$

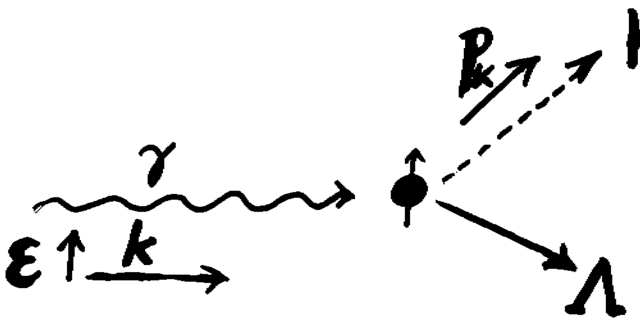
$$\left.\frac{d\sigma}{d\Omega}\right|_{2\mathrm{CM}} = \frac{q}{\kappa}\Big\{|F_1|^2 + |F_2|^2 - 2\cos\theta_{\mathrm{CM}}\,\mathrm{Re}(F_1^* F_2)$$

$$+ \frac{1}{2}\sin^2\theta_{\mathrm{CM}}[|F_3|^2 + |F_4|^2 + \mathrm{Re}(F_1^* F_4 + F_2^* F_3 + F_3^* F_4 \cos\theta_{\mathrm{CM}})]\Big\} , \quad (2\cdot2)$$

$$\mathcal{P}_Y \left.\frac{d\sigma}{d\Omega}\right|_{2\mathrm{CM}} = \frac{q}{\kappa}\sin\theta_{\mathrm{CM}}\,\mathrm{Im}\Big\{-2F_1^* F_2 - F_1^* F_3 + F_2^* F_4 + \sin^2\theta_{\mathrm{CM}} F_3^* F_4$$

$$+ \cos\theta_{\mathrm{CM}}[F_2^* F_3 - F_1^* F_4]\Big\} , \quad (2\cdot3)$$

$\{F_i\}$ CGLN type amplitudes (complex)



ε: photon polarization

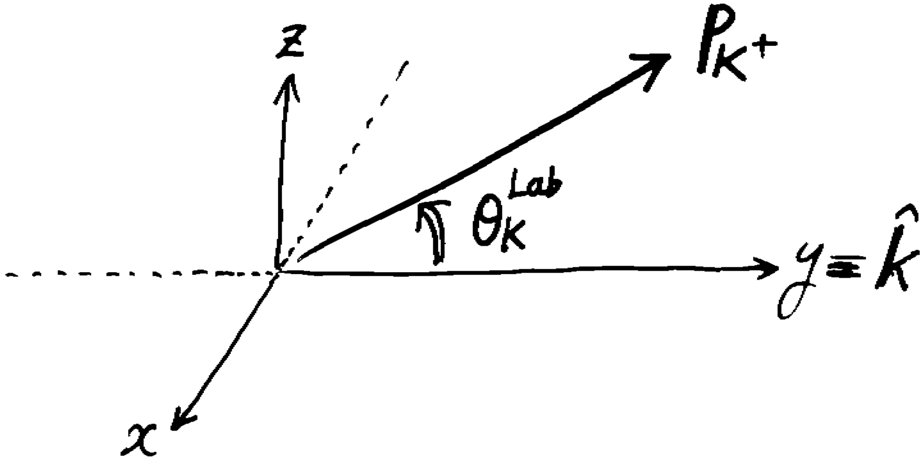
σ: Pauli spin of baryon

Lab: $$\mathcal{M} = a_1(\sigma\cdot\varepsilon) + a_2(\sigma\cdot\hat{k})(\hat{p}_K\cdot\varepsilon) + a_3(\sigma\cdot\hat{p}_K)(\hat{p}_K\cdot\varepsilon) + a_4(\hat{k}\times\hat{p}_K)\cdot\varepsilon$$

$\{F_i\}_{CM} \longrightarrow \{a_i\}_{Lab}$

$\downarrow$ New frame

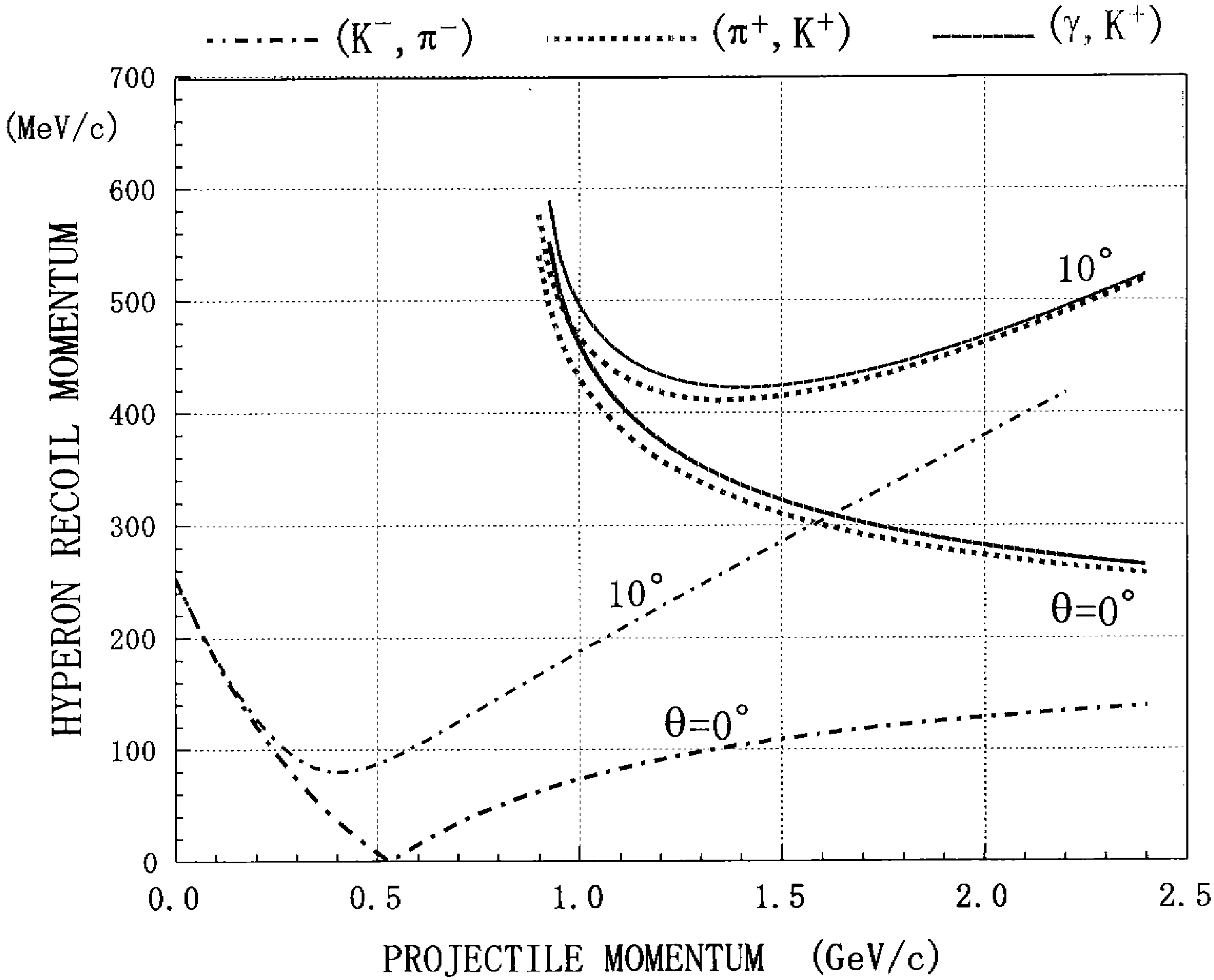
$\{f_0, g_{0,\pm1}\}_{Lab}$



$$\mathcal{M} \equiv \varepsilon_0(f_0 + g_0\sigma_0) + \varepsilon_x(g_1\sigma_{+1} + g_{-1}\sigma_{-1})$$

Cross section: $$\frac{d\sigma}{d\Omega} \propto \left[\,|f_0|^2 + |g_0|^2 + |g_1|^2 + |g_{-1}|^2\,\right]$$

Polarization: $$P\frac{d\sigma}{d\Omega} \propto \left[\,2\mathrm{Re}(f_0 g_0^*) + |g_1|^2 - |g_{-1}|^2\,\right]$$



(γ, K⁺)

q_{Λ}=350-420 MeV/c at E_{γ}=1.3 GeV

Numerical comparison of f and g's (E_γ=1.3 GeV)

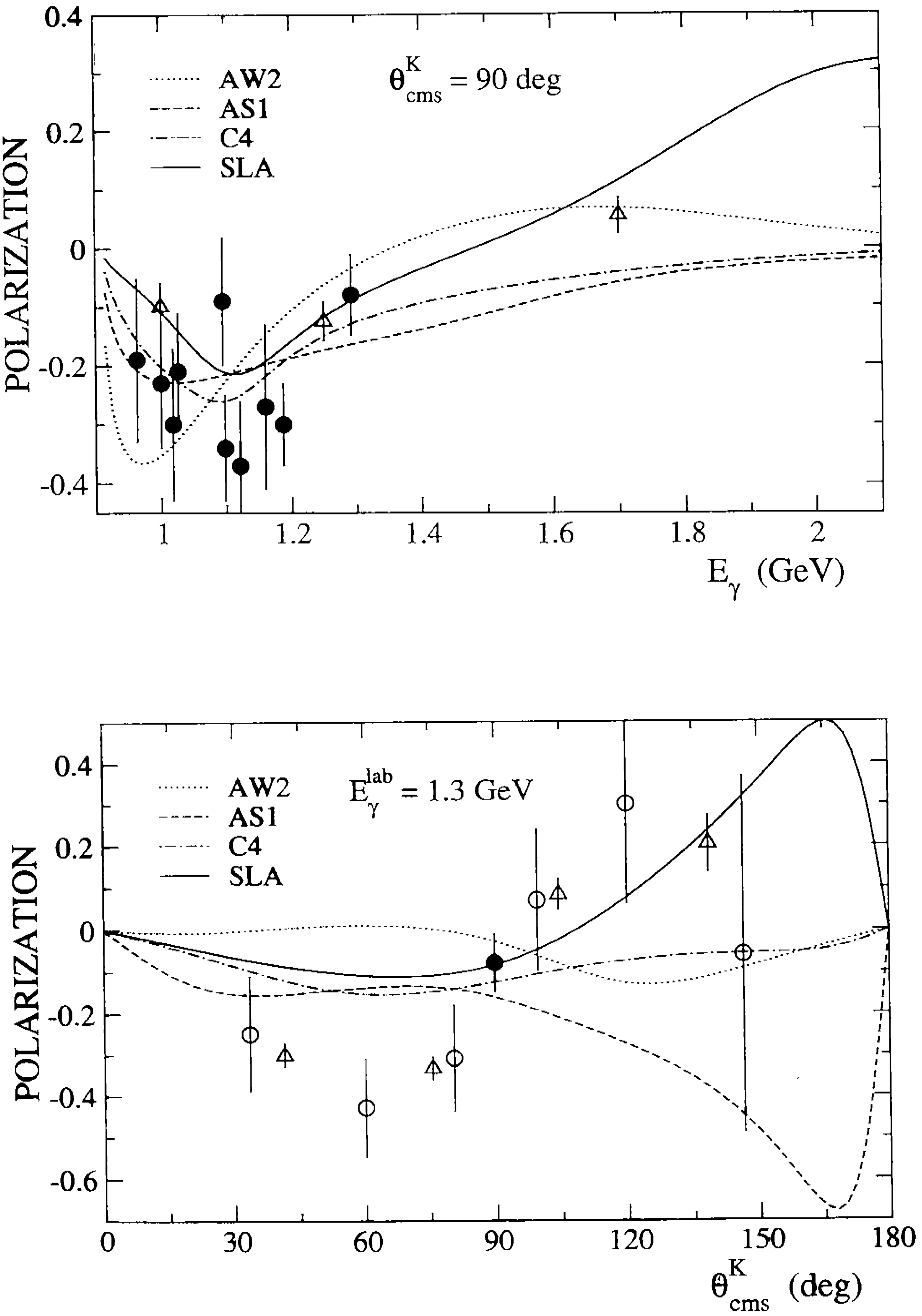
	MODEL	$\lvert f_0\rvert^2$	$\lvert g_0\rvert^2$	$\lvert g_{+1}\rvert^2$	$\lvert g_{-1}\rvert^2$	$d\sigma/d\Omega$	Pol(Λ)
θ_K=3	AS1	0.007	0.398	0.191	0.209	1.91	−0.055
	AW2	0.0001	0.369	0.188	0.192	1.78	−0.005
	C4	0.0002	0.609	0.290	0.299	2.85	−0.019
	SLA	0.002	0.451	0.224	0.222	2.14	−0.016
θ_K=10	AS1	0.055	0.375	0.175	0.205	1.84	−0.142
	AW2	0.001	0.296	0.209	0.218	1.65	−0.007
	C4	0.001	0.569	0.190	0.217	2.23	−0.066
	SLA	0.026	0.392	0.186	0.178	1.78	−0.053
						(μb/sr)	

AS1: Adelseck-Saghai (1990)
AW2: Adelseck-Wright (1988)
C4: Williams-Ji-Cotanch (1992)
SLA: Mizutani-Fayard-Lamot-Saghai (1998)
(cf. Bennhold-Mart)

@ Spin-nonflip term very small, Spin-flip 3 terms dominate.

@ Momemtum transfer: similar to $q(\pi+, K+)$. → unnatural parity high-spin states

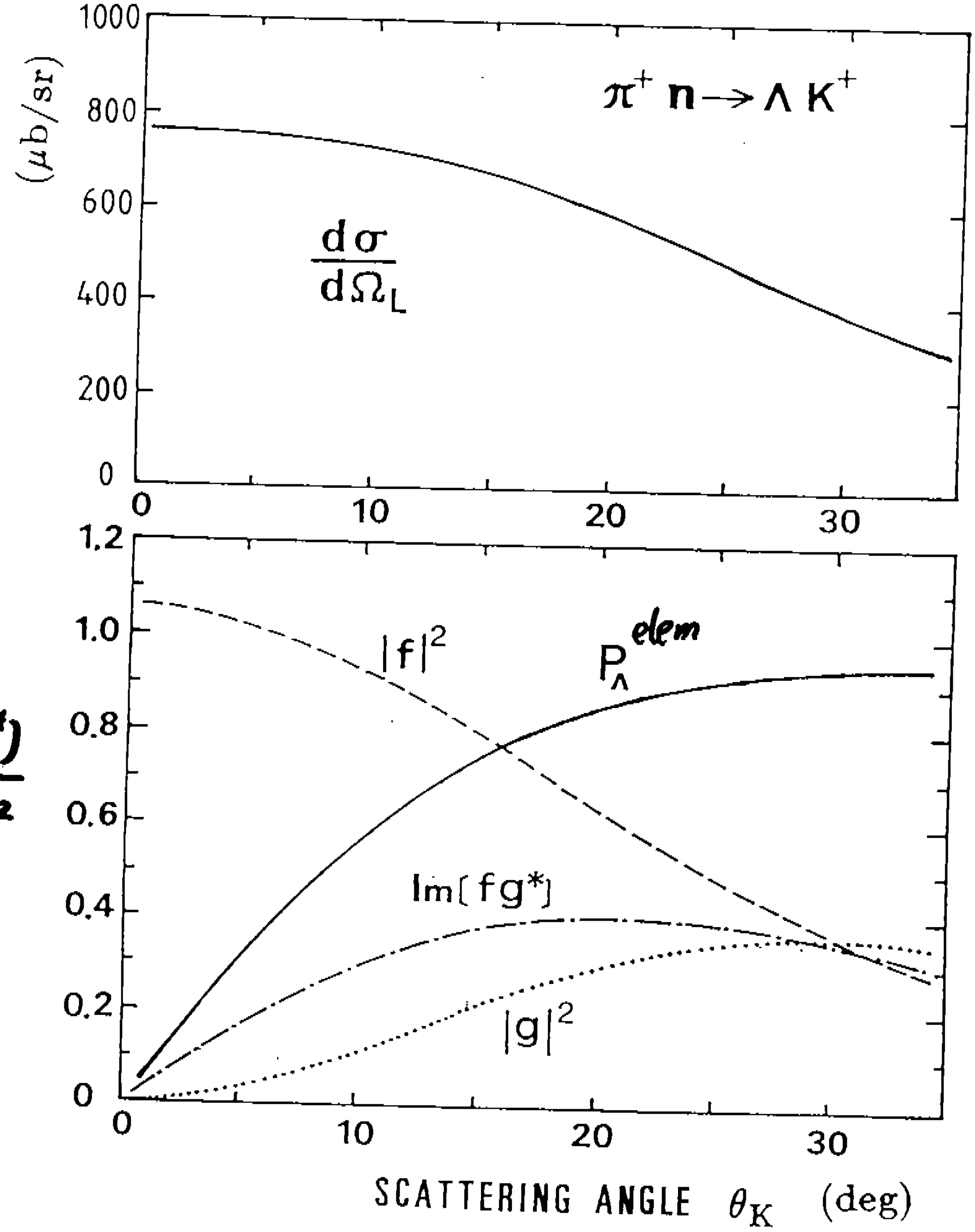
@ Appreciable difference among models esp. for $d\sigma/d\Omega$ and pol(Λ).



POLARIZATION
AW2
AS1
C4
SLA
θ^K_{cms} = 90 deg
E_γ (GeV)
POLARIZATION
AW2
AS1
C4
SLA
E_γ^{lab} = 1.3 GeV
θ^K_{cms} (deg)

$\pi^+ n \to \Lambda K^+$ $\quad f + ig(\sigma \cdot n)$

$\frac{d\sigma}{d\Omega} = 761 \quad 753 \quad 724 \quad 667 \quad 583 \quad 486 \quad 385 \quad 273$



$$P_\Lambda^{elem} = \frac{2\,\mathrm{Im}(fg^*)}{|f|^2 + |g|^2}$$

$P_\Lambda = \quad 0.32 \quad 0.57 \quad 0.75 \quad 0.85 \quad 0.91 \quad 0.94$

Fig. 8

For the hypernuclear production reaction on a nuclear target, $\gamma+A(J_i)\to H(J_f)+K^+$, the differential cross section in the lab frame is expressed analogously by

$$\left.\frac{d\boldsymbol{\sigma}}{d\boldsymbol{\Omega}}\right|_{A\text{-Lab}}=\frac{(2\pi)^4 p^2 E_K E_\gamma E_H}{k\{p(E_H+E_K)-kE_K\cos\theta_L\}}\overline{|\boldsymbol{T}_{if}^{\mathrm{Lab}}|^2}\,, \tag{2·6}$$

$$\overline{|\boldsymbol{T}_{if}^{\mathrm{Lab}}|^2}=\sum_{M_f}\boldsymbol{R}(J_iJ_f;M_f)\,, \tag{2·7}$$

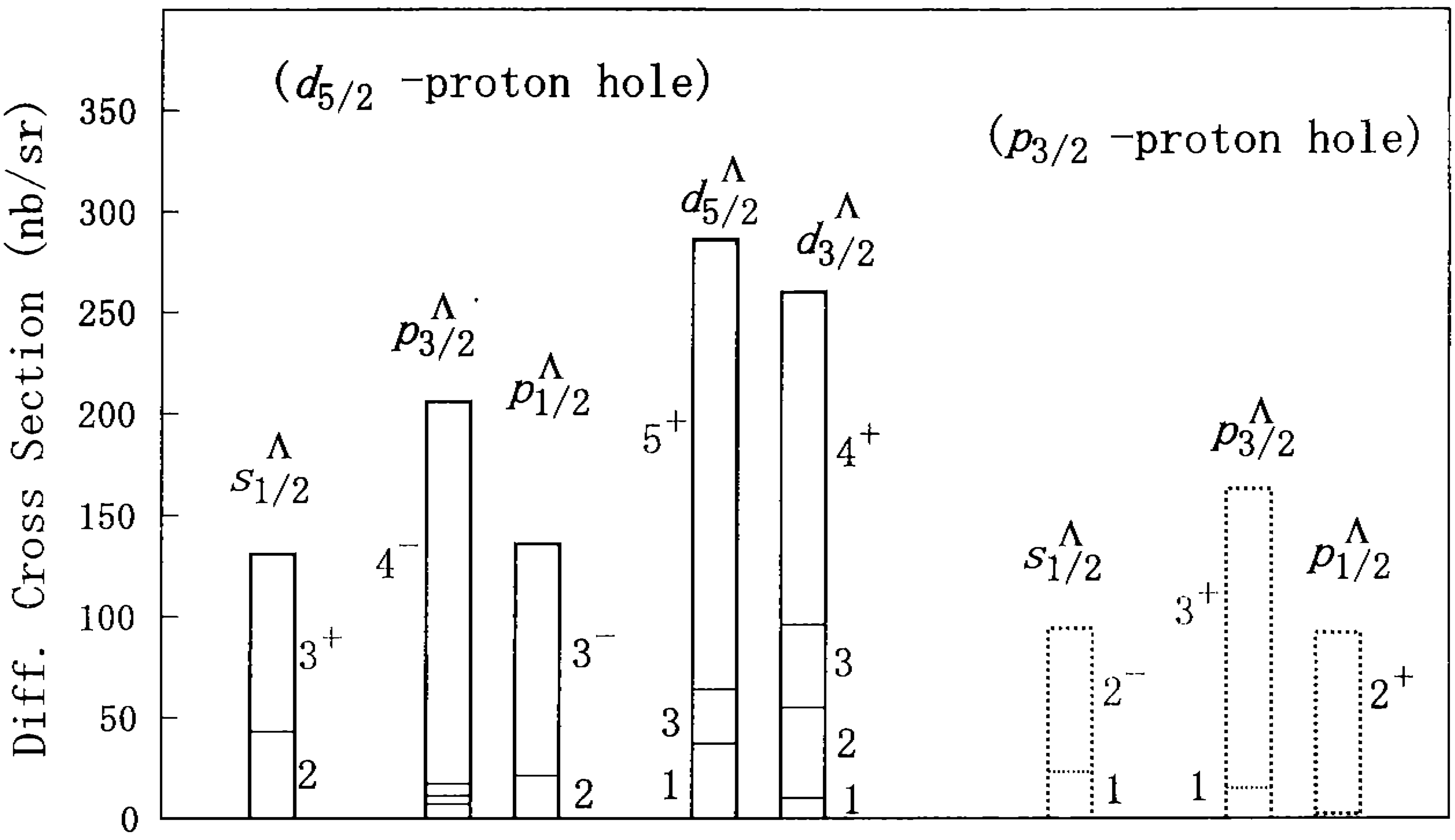
$$\boldsymbol{R}(J_iJ_f;M_f)=\frac{1}{2J_i+1}\sum_{\epsilon,M_i}\left|\langle J_fM_f|\boldsymbol{\mathcal{O}}_{\gamma K}(\theta)|J_iM_i\rangle\right|^2. \tag{2·8}$$

$$\boldsymbol{\mathcal{O}}_{\gamma K}(\theta)=\int d^3r\,\chi_K{}^{(-)*}(\boldsymbol{p},\xi\boldsymbol{r})\chi_\gamma{}^{(+)}(\boldsymbol{k},\boldsymbol{r})\sum_{\nu=1}^{A}V_-(\nu)\delta(\boldsymbol{r}-\eta\boldsymbol{r}_\nu)\langle\boldsymbol{k}-\boldsymbol{p},\boldsymbol{p}|t|\boldsymbol{k},0\rangle_L\,. \tag{2·9}$$

$$\mathcal{P}_H(J_f)=\sum_{M_f}\frac{M_f}{J_f}\frac{\boldsymbol{R}(J_iJ_f;M_f)}{\tilde{\boldsymbol{R}}(J_iJ_f)}\quad\text{with }\tilde{\boldsymbol{R}}(J_iJ_f)=\sum_{M_f}\boldsymbol{R}(J_iJ_f;M_f)\,. \tag{2·10}$$

$\chi_K^{(-)}$: Distorted wave ← Klein-Gordon Eq.

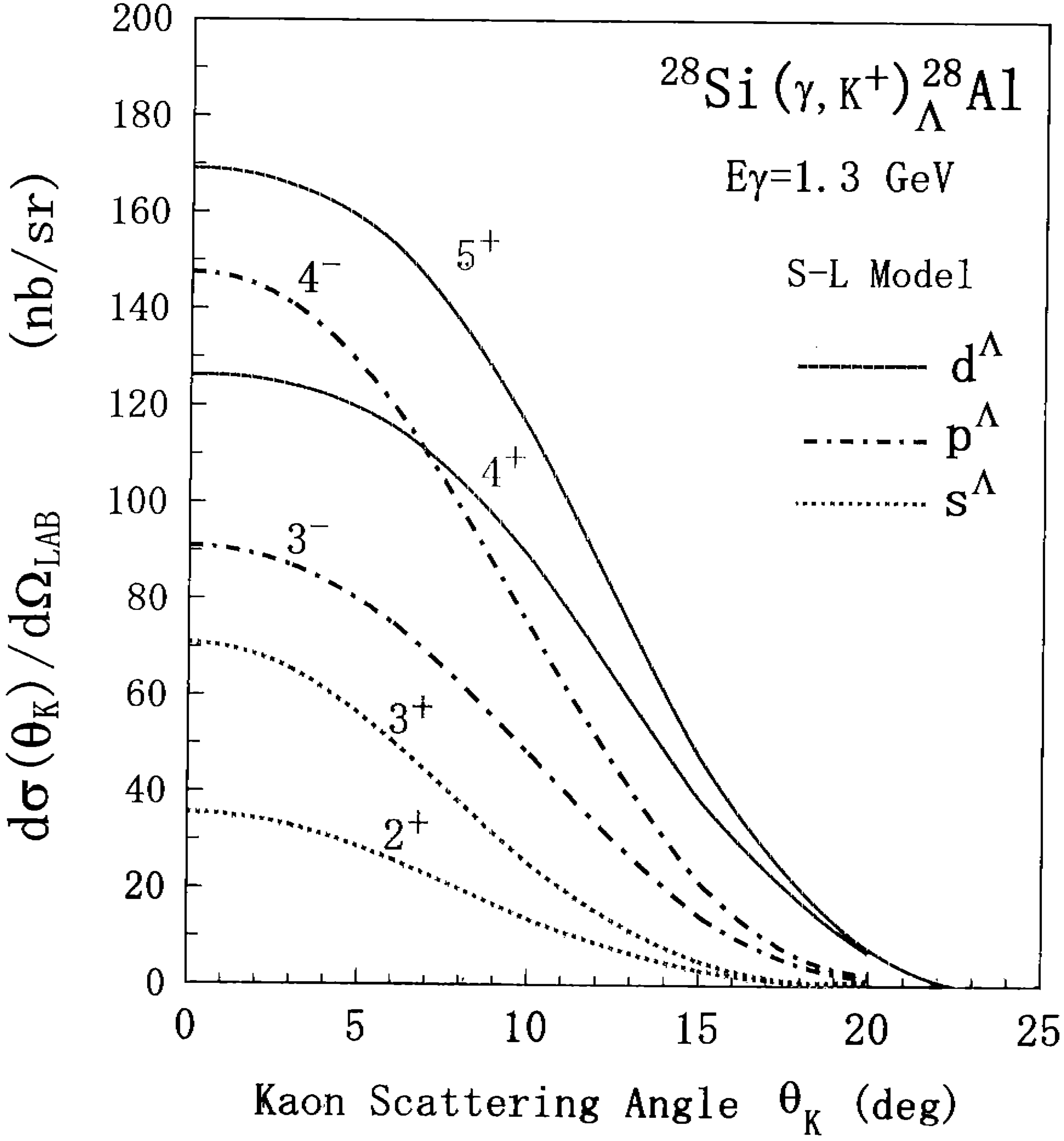
Contents of ^{28}Si(γ, K$^+$) spectrum $(d_{5/2})^{12}$ MODEL



Selective Excitation

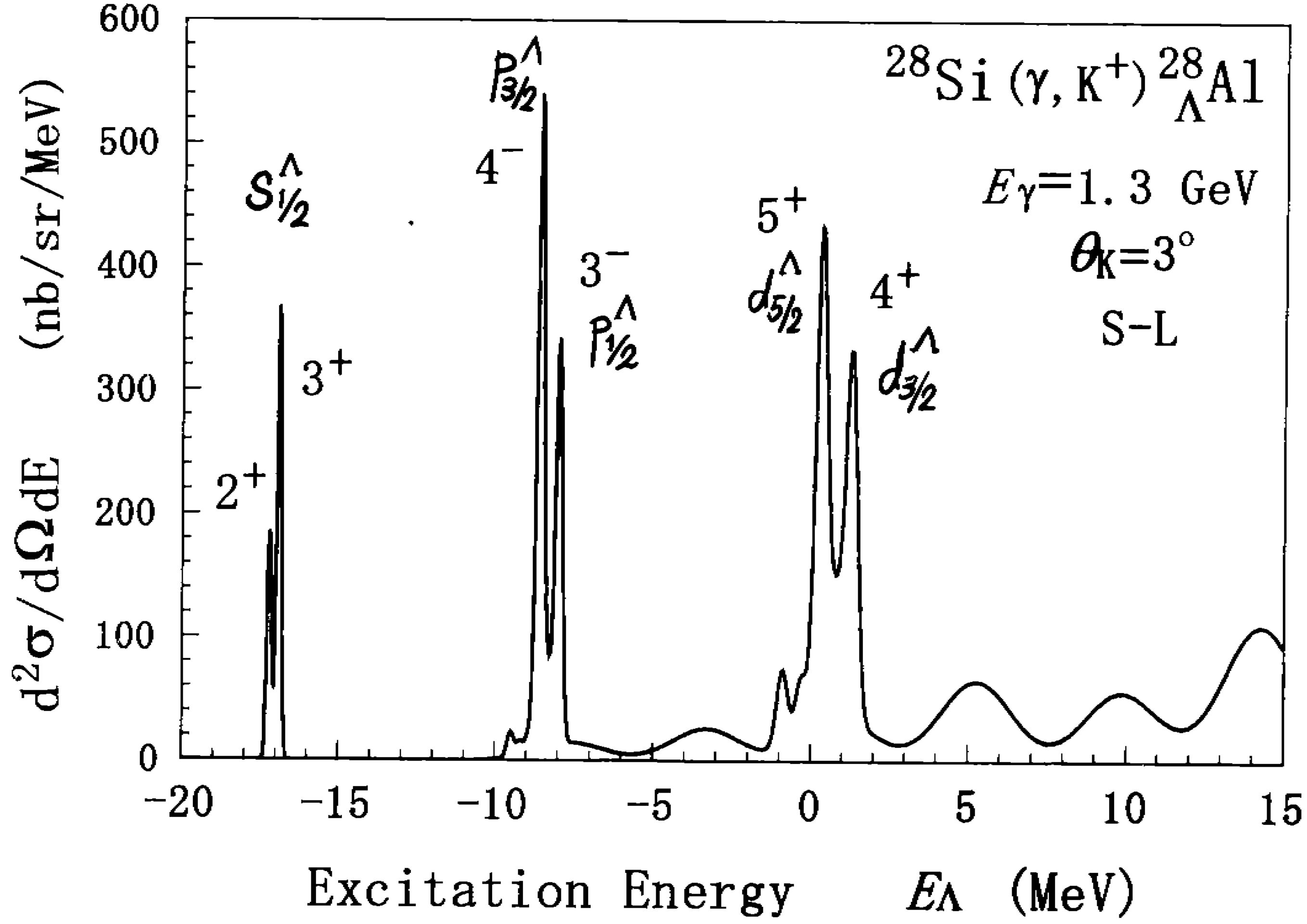
$[j_{>}^{-1} j_{>}^{\Lambda}]$: $J_{max} = j_{>} + j_{>}^{\Lambda} = l_N + l_{\Lambda} + 1 = L_{max} + 1$ unnatural parity

$[j_{>}^{-1} j_{<}^{\Lambda}]$ or $[j_{<}^{-1} j_{>}^{\Lambda}]$: $J'_{max} = l_N + l_{\Lambda} = L_{max}$ natural parity

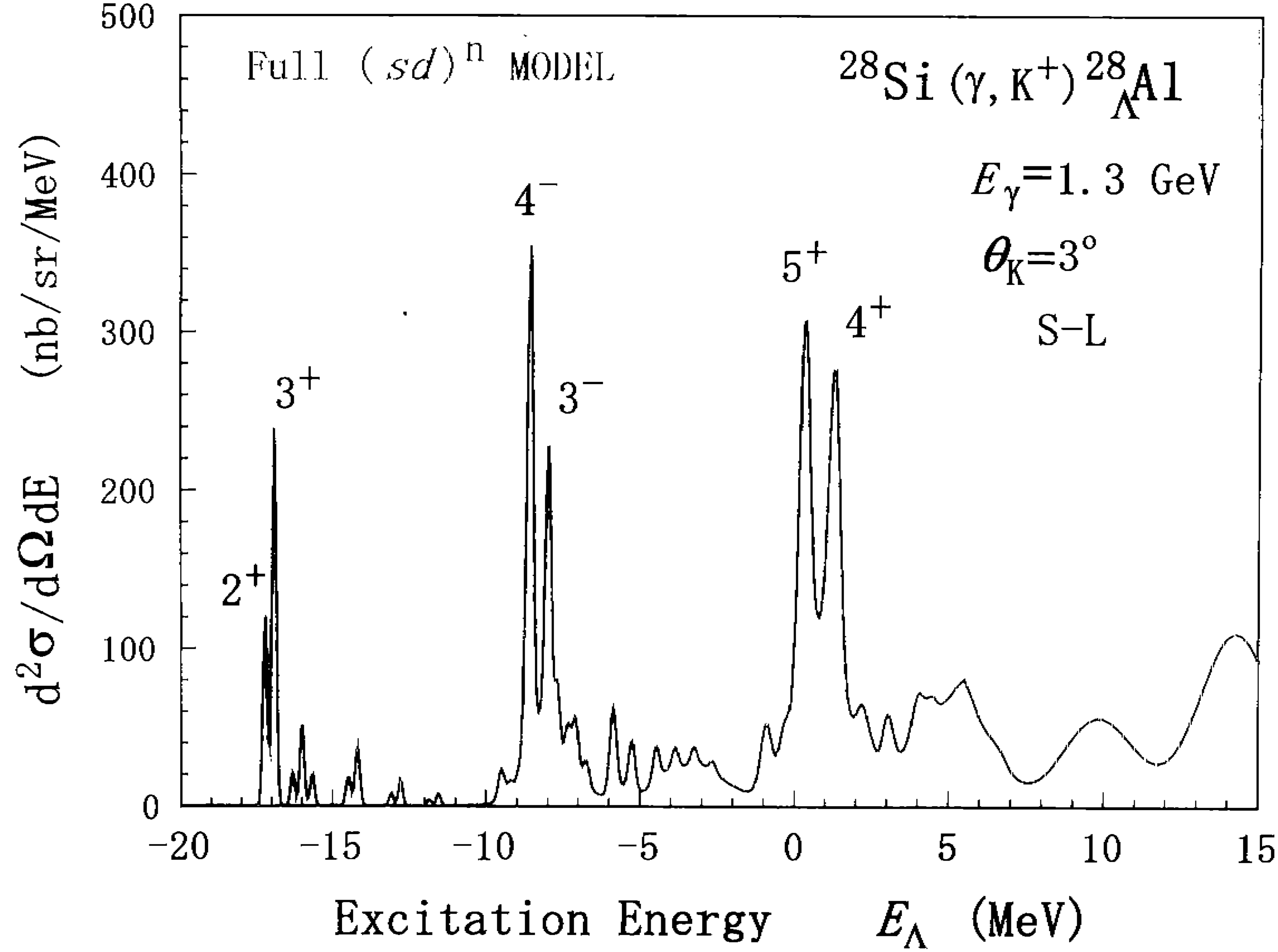


$(sp)^{16}(d_{5/2})^{12}$

Model



$^{28}Si(\gamma, K^+)^{28}_{\Lambda}Al$
E_γ=1.3 GeV
θ_K=3°
S-L
$s_{1/2}^{\Lambda}$
$p_{3/2}^{\Lambda}$
$p_{1/2}^{\Lambda}$
$d_{5/2}^{\Lambda}$
$d_{3/2}^{\Lambda}$
2^+
3^+
4^-
3^-
5^+
4^+
$d^2\sigma/d\Omega dE$ (nb/sr/MeV)
0
100
200
300
400
500
600
−20
−15
−10
−5
0
5
10
15
Excitation Energy E_Λ (MeV)



1) A series of major peaks in the $(d_{5/2})^{12}$ model persist.

2) Their cross sections are approx. 0.65 x ($d_{5/2}$ model).

3) New substates are expected based on ^{27}Al-core excitation.

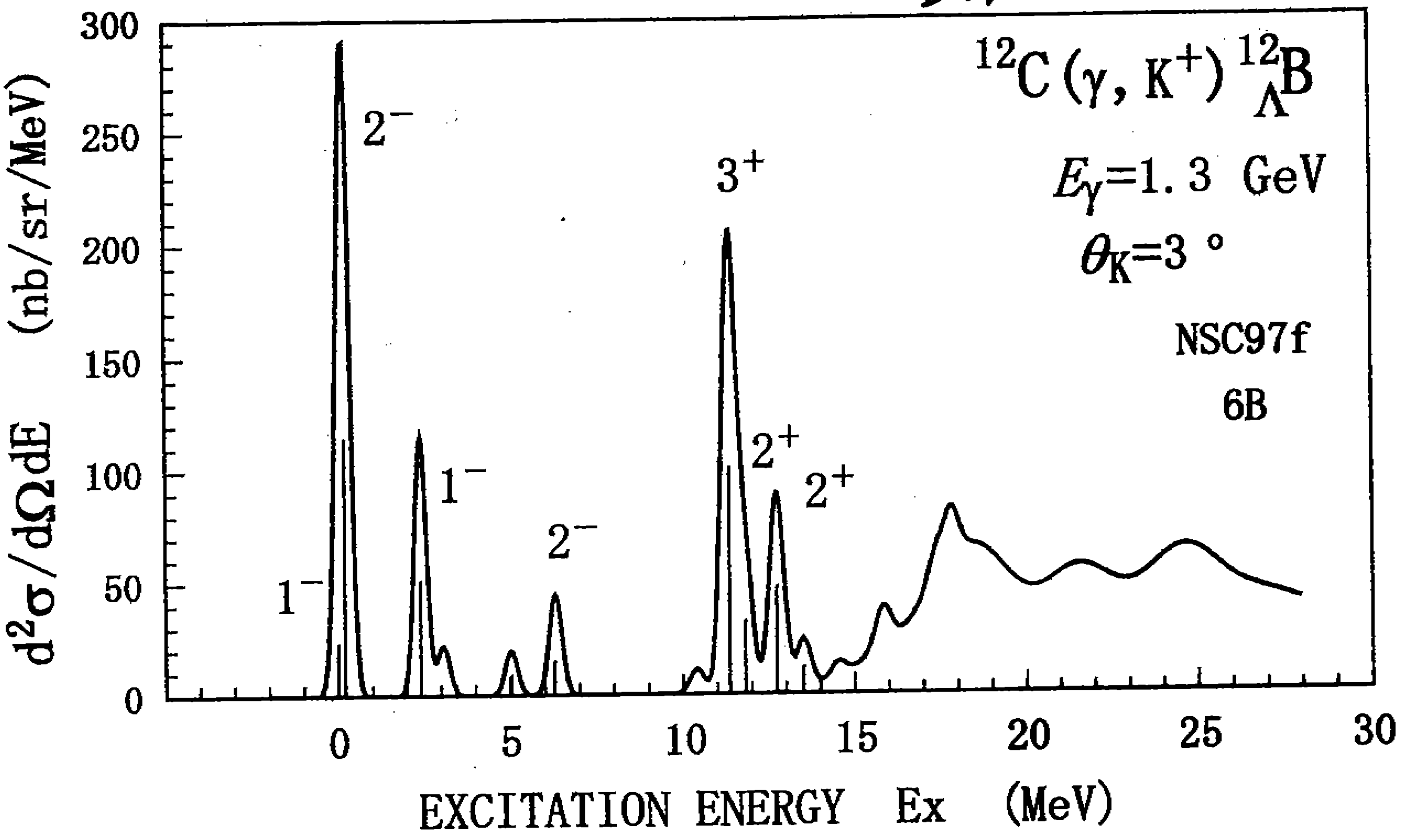
Photo/Electro-production of p-shell hypernuclei:

${}^{7}Li(\gamma,K^+){}^{7}_{\Lambda}He$	$T=1$, n-halo	
${}^{9}Be(\gamma,K^+){}^{9}_{\Lambda}Li$	$T=1$	
${}^{10}B(\gamma,K^+){}^{10}_{\Lambda}Be$		$T=1/2$ mirror of ${}^{10}_{\Lambda}B$ (π^+,K^+)
${}^{11}B(\gamma,K^+){}^{11}_{\Lambda}Be$	$T=1$	
${}^{12}C(\gamma,K^+){}^{12}_{\Lambda}B$	EXP	$T=1/2$ mirror of ${}^{12}_{\Lambda}C$
${}^{13}C(\gamma,K^+){}^{13}_{\Lambda}B$	$T=1$	
${}^{14}N(\gamma,K^+){}^{14}_{\Lambda}C$		$T=1/2$ mirror of ${}^{14}_{\Lambda}N$
${}^{16}O(\gamma,K^+){}^{16}_{\Lambda}N$		$T=1/2$ mirror of ${}^{16}_{\Lambda}O$

Interests:

- proton-defficient hyp. { $T=1$ (n-rich), $T=1/2$ (mirror) }
- Λ dynamical coupling with core-excited states
- unified knowledge of p-h multiplets → detailed information of $v_{\Lambda N}$
- structure change of light systems (such as shrinkage)

DWIA



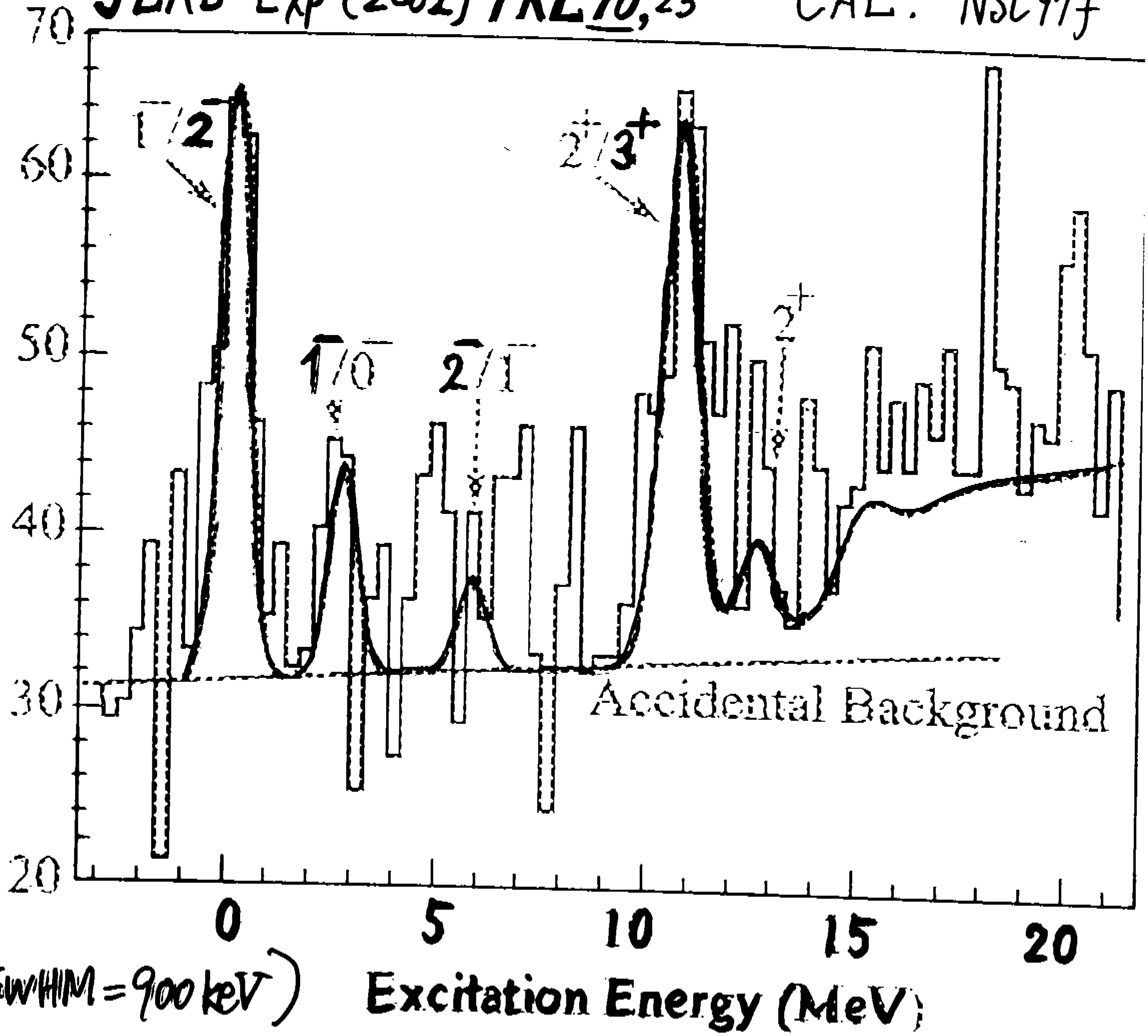
C12gk6B97f

Motoba-Sotona-Itonaga, Prog. Theor. Phys. Suppl. 117, 127 (1994)

Motoba, Mesons & Light Nuclei (2000) updated.

n below ~ 12 MeV, but statistics are insufficient
ly resolve the structure.

JLAB Exp (2002) PRL 90, 23 (2003) CAL: NSC97f



3: The summed $^{12}_{\Lambda}B$ missing mass spectrum for bo
ies

$[p_{3/2}^{-1} p_{3/2}^{\Lambda}]_J$

$J=0^+$ (K^-,π^-)
1^+ $(K^-,\pi^-)_{\theta\gg1}$
2^+ (π^+,K^+)
3^+ (γ,K^+)

3^+ $[p_{3/2}^{-1} p_{3/2}^{\Lambda}]$
$|g_1|^2-|g_{-1}|^2$
2^- $[p_{3/2}^{-1} s_{1/2}^{\Lambda}]$

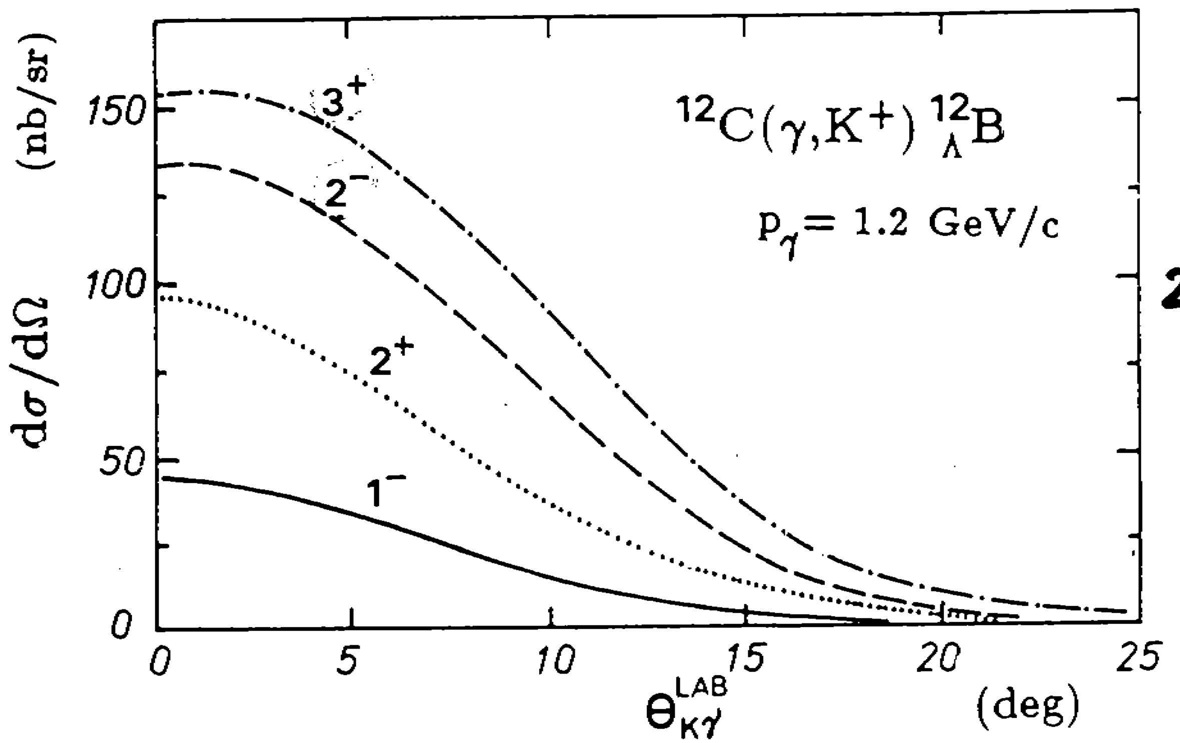


Fig. 4.2. Calculated (γ, K^+) cross sections for the $[0p_{3/2}^{-1}0s_{1/2}^{\Lambda}]_{J=1^-,2^-}$ and $[0p_{3/2}^{-1}0p^{\Lambda}]_{J=2^+,3^+}$ shell model states describing $^{12}_{\Lambda}B$.

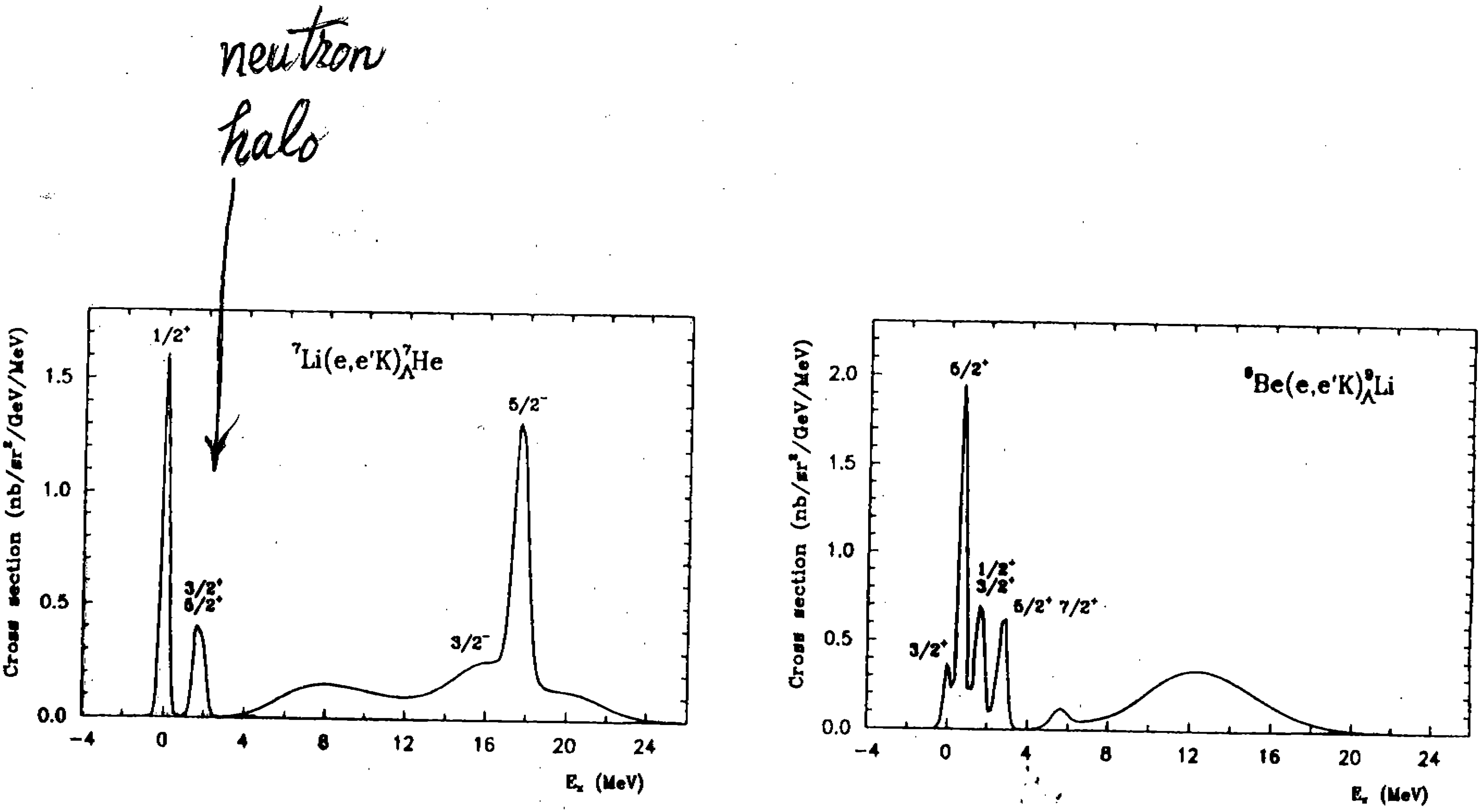
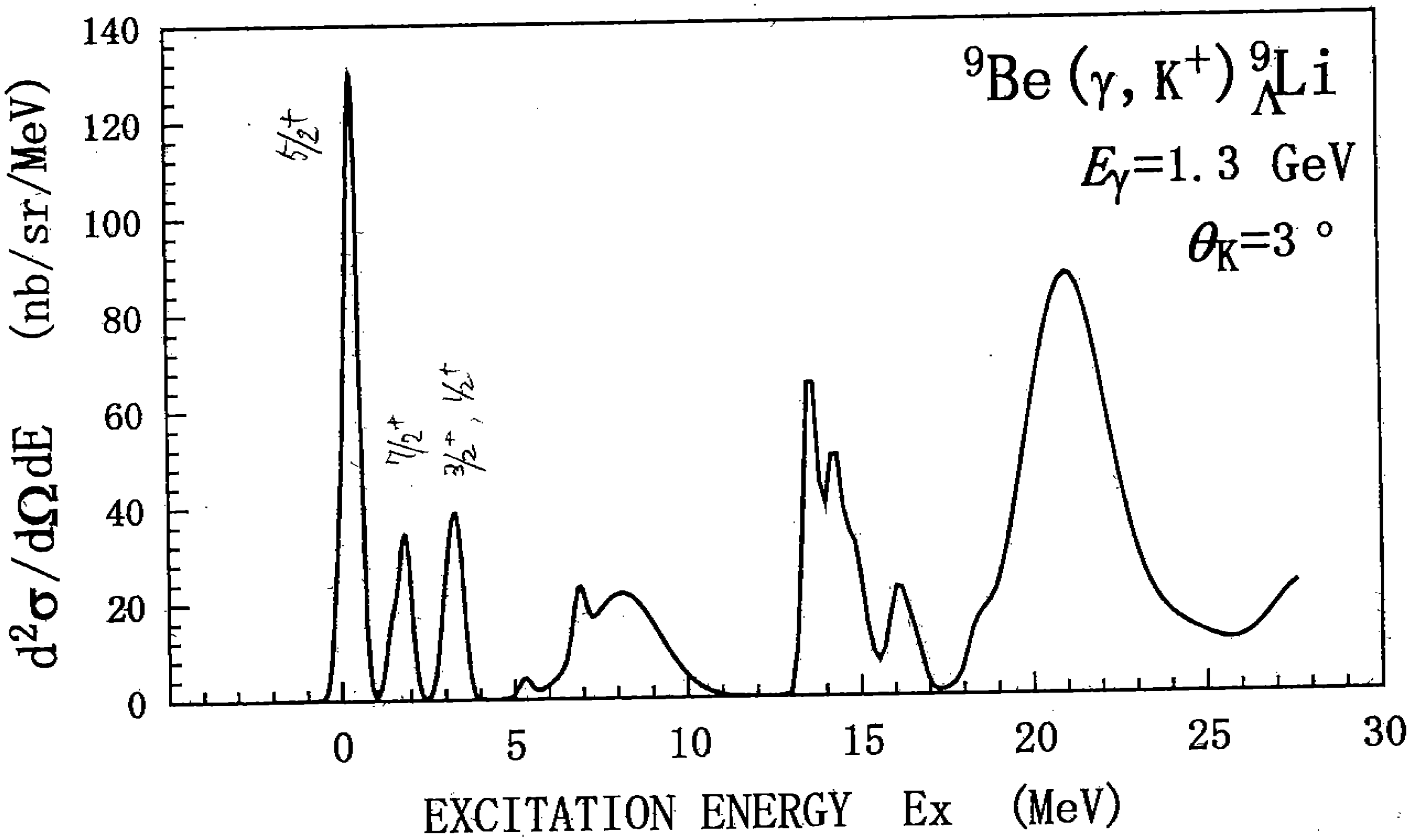
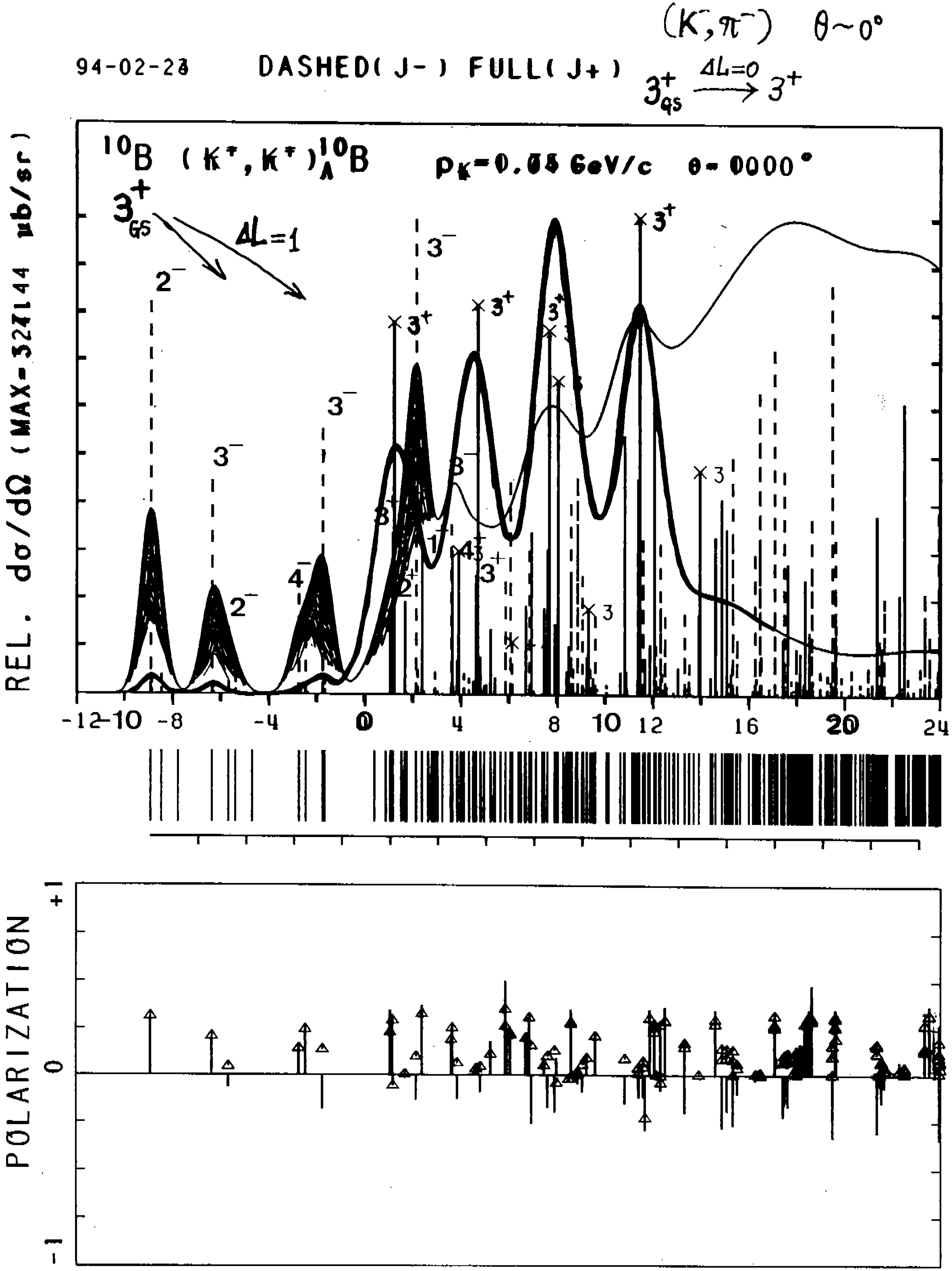


Figure 2: Hypernuclear excitation functions at $E_e = 4.0$ GeV, $E'_e = 1.8$ GeV, $\theta_e = \theta_{Ke} = 6^o$ for ^{7}Li target (left) and ^{9}Be target (right).

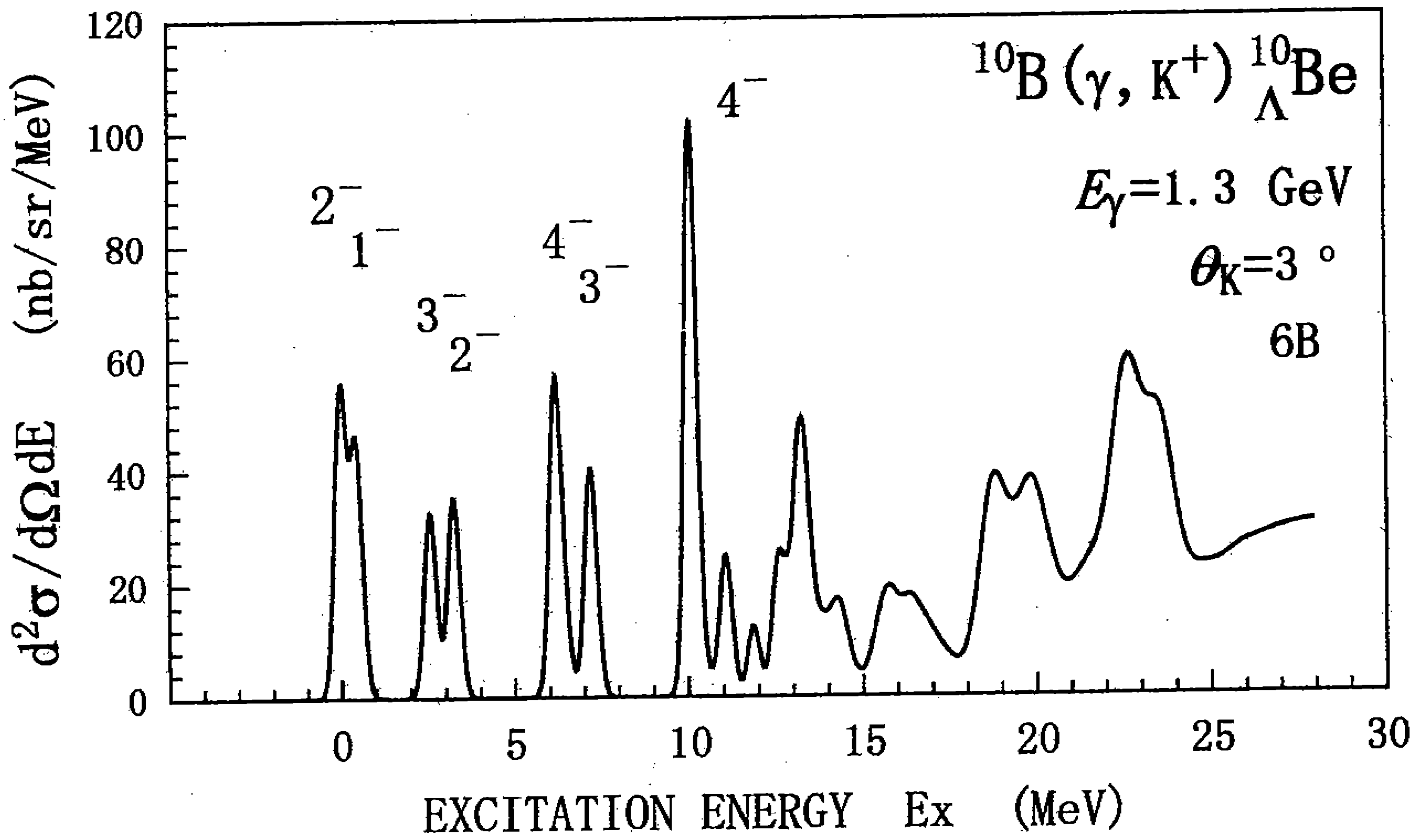


$^9Be(\gamma, K^+)^9_\Lambda Li$
E_γ=1.3 GeV
θ_K=3 °
d²σ/dΩdE (nb/sr/MeV)
EXCITATION ENERGY Ex (MeV)
0
20
40
60
80
100
120
140
5
10
15
25
30

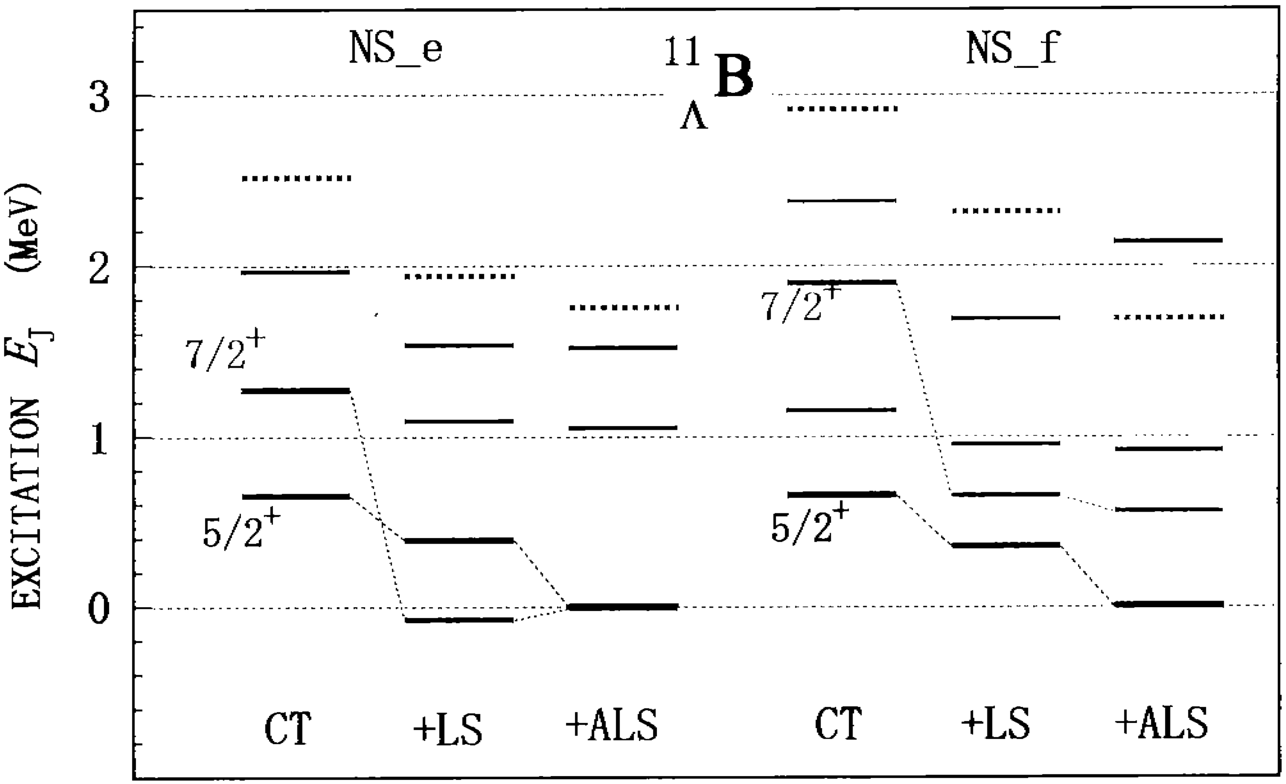
Be9gk6B



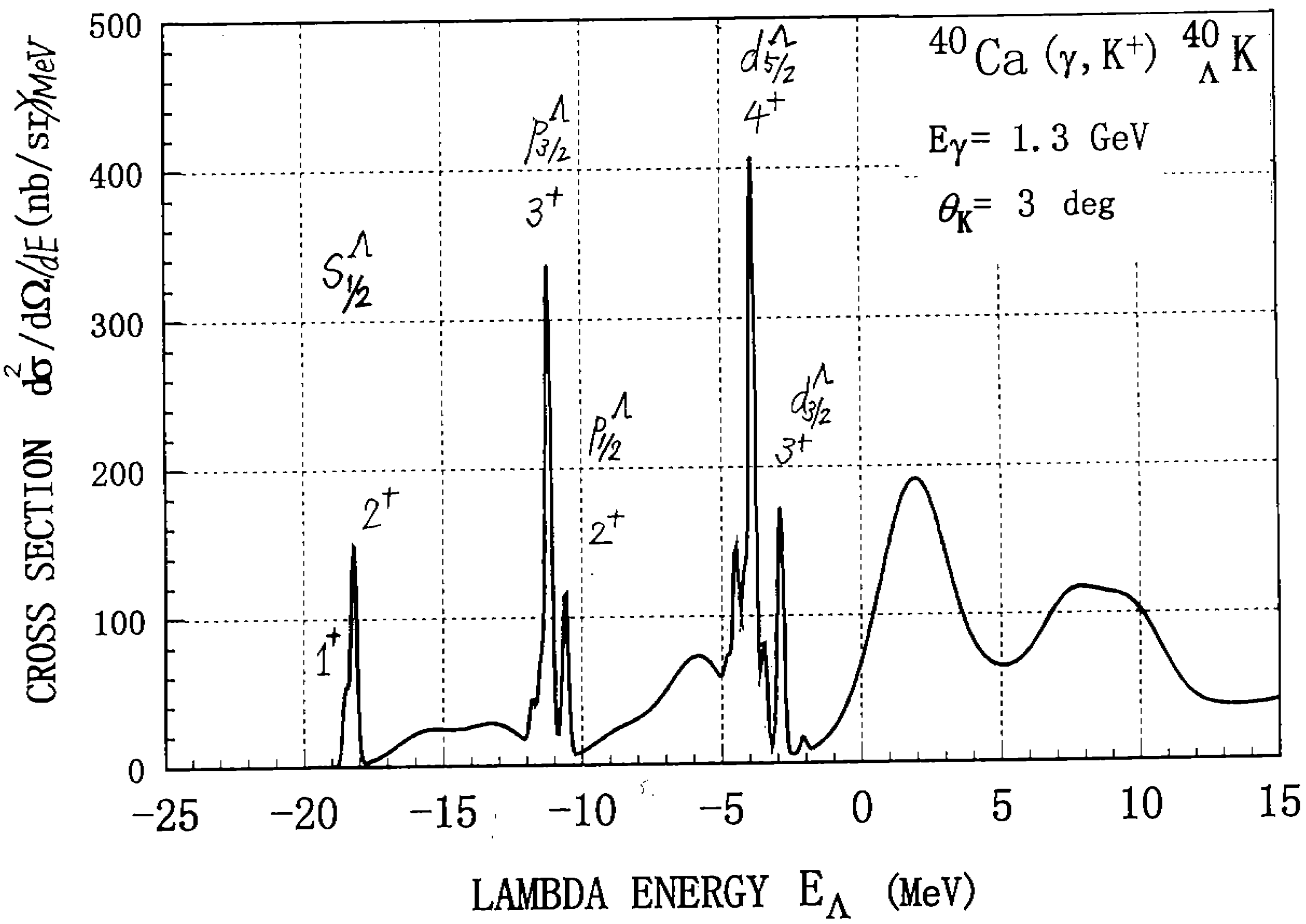
94-02-23 23:23:42 S0540374 502


$^{10}B(\gamma, K^+)\,^{10}_{\Lambda}Be$
E_γ=1.3 GeV
θ_K=3 °
6B
2^-
1^-
3^-
2^-
4^-
3^-
4^-
$d^2\sigma/d\Omega dE$ (nb/sr/MeV)
0
20
40
60
80
100
120
0
5
10
15
20
25
30
EXCITATION ENERGY Ex (MeV)

B1

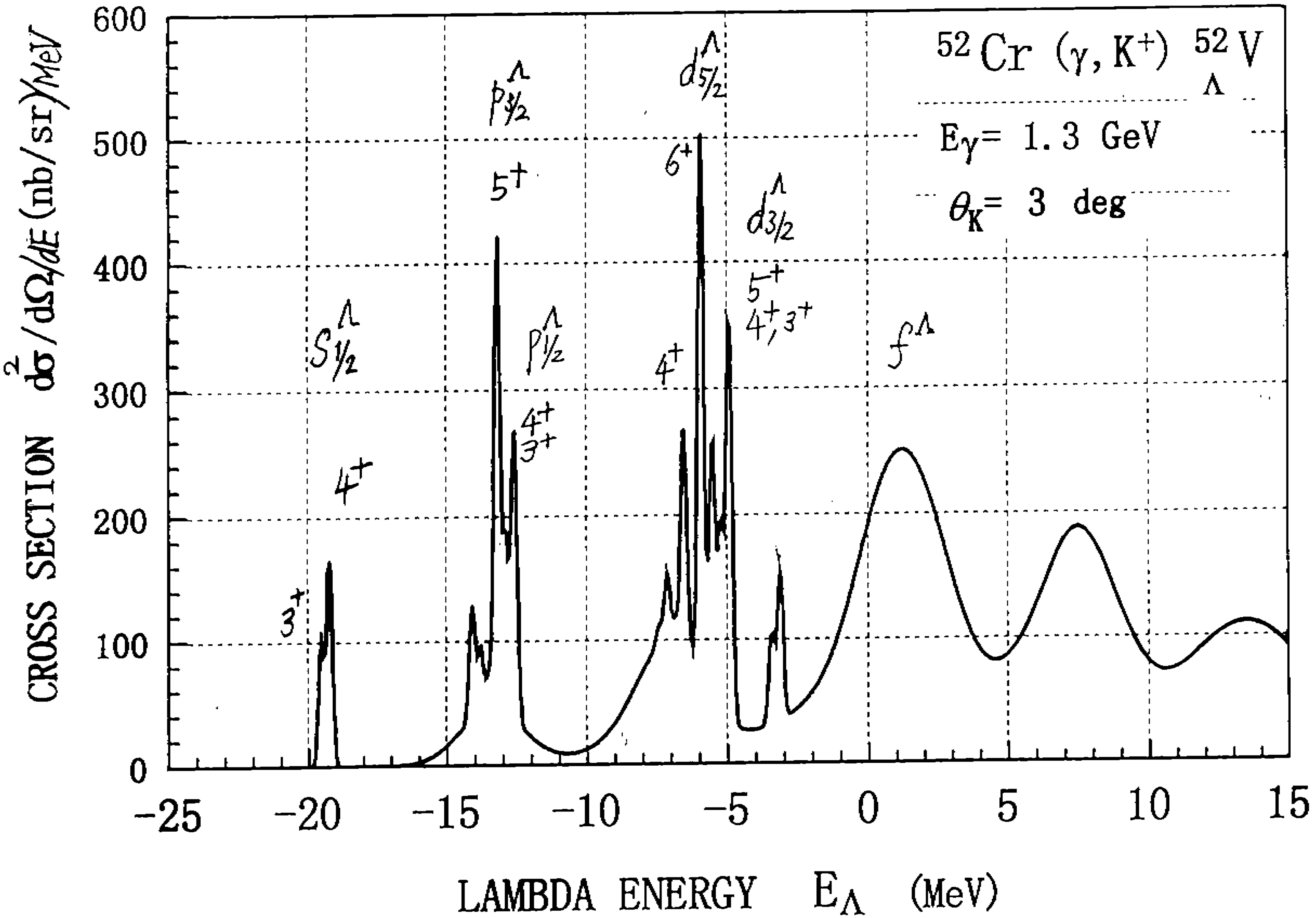

NS_e
11 Λ B
NS_f
3
2
1
0
EXCITATION E_J (MeV)
7/2+
5/2+
7/2+
5/2+
CT
+LS
+ALS
CT
+LS
+ALS

B11_CTL



^{40}Ca (γ, K$^+$) $^{40}_{\Lambda}$K
Eγ= 1.3 GeV
θ_K= 3 deg
CROSS SECTION $d^2\sigma/d\Omega/dE$ (nb/sr/MeV)
LAMBDA ENERGY E_Λ (MeV)
0
100
200
300
400
500
−25
−20
−15
−10
−5
0
5
10
15
$s_{1/2}^{\Lambda}$
1^+
2^+
$p_{3/2}^{\Lambda}$
3^+
$p_{1/2}^{\Lambda}$
2^+
$d_{5/2}^{\Lambda}$
4^+
$d_{3/2}^{\Lambda}$
3^+

A40gs7



^{52}Cr (γ, K$^+$) $^{52}_{\Lambda}$V
Eγ= 1.3 GeV
θ_K= 3 deg
CROSS SECTION $d^2\sigma/d\Omega/dE$ (nb/sr)/MeV
LAMBDA ENERGY E_Λ (MeV)
600
500
400
300
200
100
0
−25
−20
−15
−10
−5
0
5
10
15

Production of A ~50 hypernuclei

$^{51}V(e,e'K^+)^{51}_{\Lambda}Ti$ E_e=4.056 GeV, $E_{e'}$=1.856 GeV,

$^{52}Cr(e,e'K^+)^{52}_{\Lambda}V$ θ_e=6 deg. → almost real photon

^{48}Ca core assumed.

Configuration: $[f^{\,n}_{7/2}] + [f^{\,n-1}_{7/2}\, p_{3/2}] + [f^{\,n-1}_{7/2}\, f_{5/2}]$

K. Lpis and M. T. McEllistrem, P. R. C1 1009 (1970)

$^{51}V(e,e'K^+)^{51}_{\Lambda}Ti$ Triple diff. x-section(nb/sr ^{2}/GeV)

Λ	E_x	J_f	SL Model	BM Model
0s	0.0	1/2+	1.298	0.849
0p	8.014	3/2-	1.577	1.462
	8.153	1/2-	2.488	0.877
0d	16.575	5/2+	1.378	1.712
	16.840	3/2+	2.468	0.410

dominantly

$^{42}Ti(0^+) \times j_{\Lambda}$

SUMMARY

1) Basic properties of the $\gamma p \to \Lambda K^+$ process are discussed with typical models for the amplitudes:

------ spin-flip domiance, large q,

------ appreciable difference among theor. models (P).

2) Novel characteristics of photo/electroproduction of hypernuclei are clarified with the ^{28}Si target: $(d_{5/2})^{12}$ Model

$[j_>^{-1}\ j_>^{\Lambda}]$: $J_{max} = j_> + j_>^{\Lambda} = l_N + l_\Lambda + 1 = L_{max} + 1$ unnatural parity

$[j_>^{-1}\ j_<^{\Lambda}], [j_<^{-1}\ j_>^{\Lambda}]$: $J'_{max} = l_N + l_\Lambda = L_{max}$ orbitally streched

Selective excitation of high-spin states, providing a series of Λ orbits.

3) A realistic calculation with the full $(sd)^n$ w.f. has been done for ^{28}Si$(\gamma, K^+)^{28}_{\Lambda}$Al, which should be compared with the coming exp. at JLab.

4) Present theoretical framework has been confirmed by the good agreement with the first hyp. data from Jlab.: ^{12}C(e,e'K+)$^{12}_{\Lambda}$B.

Show possibility of producing "p-defficient" p-shell hypernuclei.

5) Extend the approach to produce heavier hypernuclei A ~50, hoping to disclose new areas.